Cosmology with Gravitational Waves

The Potential of the eLISA mission

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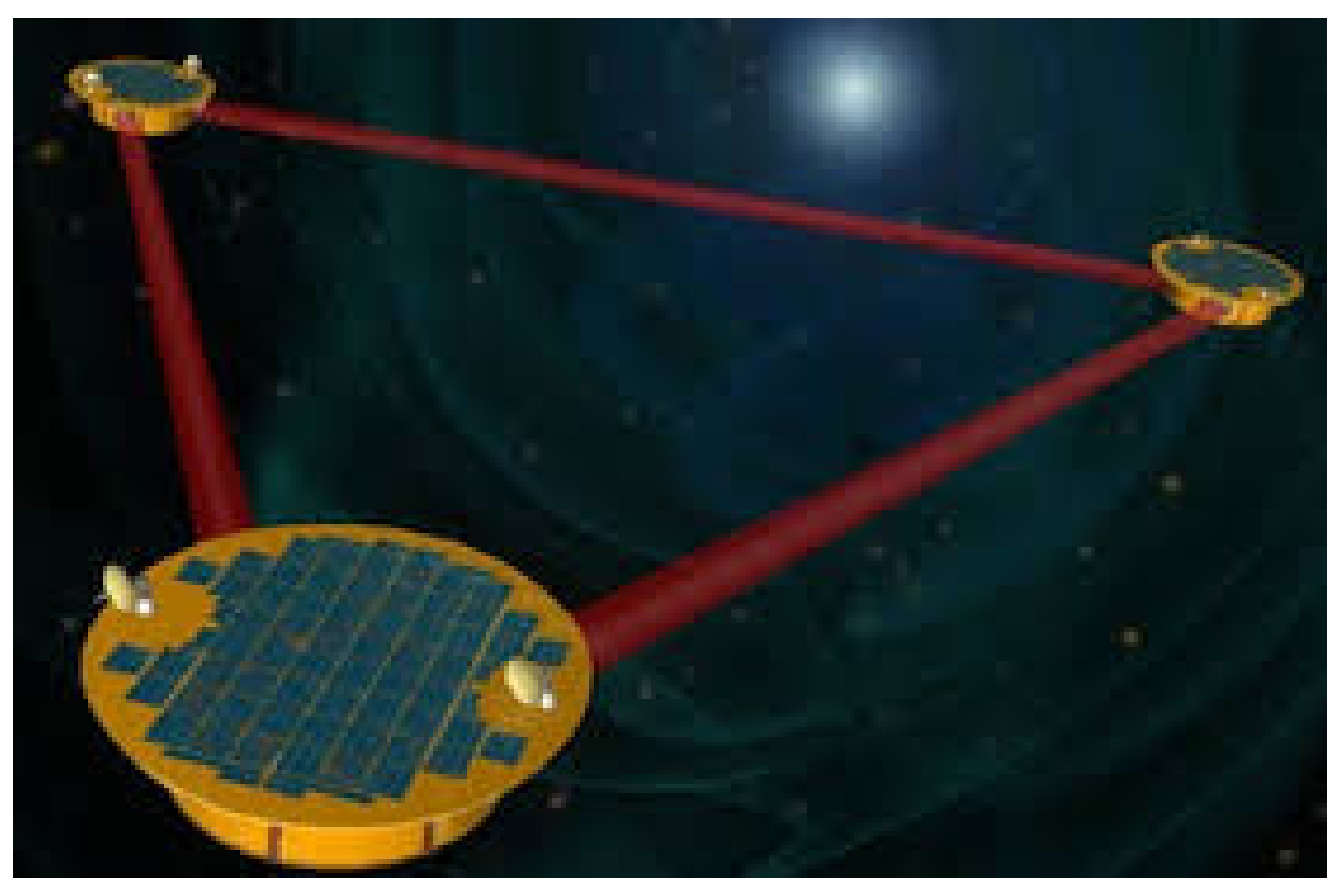
Abstract

We investigated the capability of various configurations of the space interferometer eLISA to probe the late-time background expansion of the universe using gravitational wave standard sirens. We simulated catalogues of standard sirens composed by massive black hole binaries whose gravitational radiation is detectable by eLISA, and which are likely to produce an electromagnetic counterpart observable by future surveys. The main issue for the identification of a counterpart resides in the capability of obtaining an accurate enough sky localisation with eLISA. This seriously challenges the capability of four-link (2 arm) configurations to successfully constrain the cosmological parameters. Conversely, six-link (3 arm) configurations have the potential to provide a test of the expansion of the universe up to $z \sim 8$ which is complementary to other cosmological probes based on electromagnetic observations only. In particular, in the most favourable scenarios, they can provide a significant constraint on H_0 at the 1% level. Furthermore, $(\Omega_M, \Omega_\Lambda)$ can be constrained to a level competitive with present SNIa results. On the other hand, the lack of massive black hole binary standard sirens at low redshift allows to constrain dynamical dark energy only at the level of few percent.

The eLISA mission

The last century has seen enormous progress in our understanding of the Universe. We know the life cycles of stars, the structure of galaxies, the remnants of the big bang, and have a general understanding of how the Universe evolved. We have come remarkably far using electromagnetic radiation as our tool for observing the Universe. However, gravity is the engine behind many of the processes in the Universe, and much of its action is dark. Opening a gravitational window on the Universe will let us go further than any alternative. Gravity has its own messenger: Gravitational waves (GWs), ripples in the fabric of spacetime. They travel essentially undisturbed and let us peer deep into the formation of the first seed black holes, exploring redshifts as large as z ∼ 20, prior to the epoch of cosmic re-ionisation. Exquisite and unprecedented measurements of black hole masses and spins will make it possible to trace the history of black holes across all stages of galaxy evolution, and at the same time constrain any deviation from the Kerr metric of General Relativity. eLISA will be the first ever mission to study the entire Universe with gravitational waves. eLISA is an all-sky monitor and will offer a wide view of a dynamic cosmos using gravitational waves as new and unique messengers to unveil the gravitational Universe. It provides the closest ever view of the early processes at TeV energies, has guaranteed sources in the form of verification binaries in the Milky Way, and can probe the entire Universe, from its smallest scales around singularities and black holes, all the way to cosmological dimensions. For more details visit elisascience.org.



eLISA main science objectives

- Astrophysics and evolution of massive black holes ($10^4 - 10^7\, M_\odot$)
- Astrophysics of ultra-compact binaries (neutron stars, white dwarfs, black holes)
- Tests of general relativity (BH geometry and horizon, speed and mass of gravitons)
- Cosmology (TeV energy scale at early-times, expansion at late-times)

The concept of standard siren

The GW signal emitted by a binary system and measured by an interferometric detector such as eLISA, directly depends on the luminosity distance (d_L) of the source

$$h_\times = \frac{4}{d_L}\left(\frac{G\mathcal{M}_c}{c^2}\right)^{\frac{5}{3}}\left(\frac{\pi f}{c}\right)^{\frac{2}{3}}\cos\iota\sin[\Phi(t)]$$

This implies that GW sources can be used as standard distance indicator. Hence if the redshift (z) of the GW sources can also be determined, then one can populate the $d_L(z)$ diagram and fit the distance-redshift relation

$$d_L(z) = \frac{c}{H_0}\frac{1+z}{\sqrt{\Omega_k}}\sinh\left[\sqrt{\Omega_k}\int_0^z \frac{H_0}{H(z')}dz'\right]$$

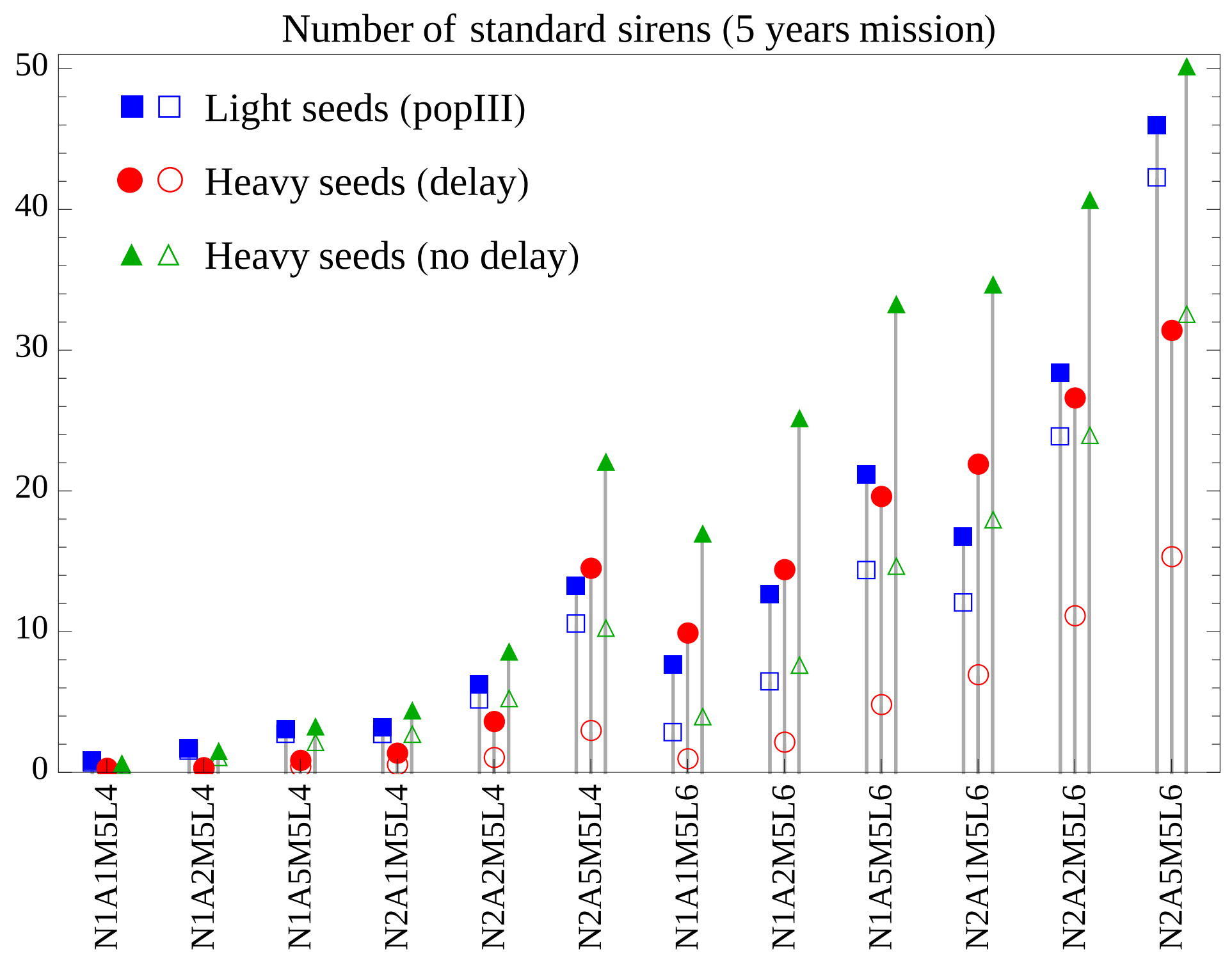
in order to constrain the cosmological parameters which characterise the Hubble rate $H(z)$. The procedure is similar to the one adopted in the discovery of dark energy in 1998, where type-Ia supernovae (SNIa), which are known as *standard candles*, were utilised. Analogously to SNIa, GW sources whose luminosity distance and redshift can both be measured, are called *standard sirens*. The main complication of this technique consists in the coincident observation of an optical counterpart from which one can measure the redshift of the source.

Standard sirens with eLISA

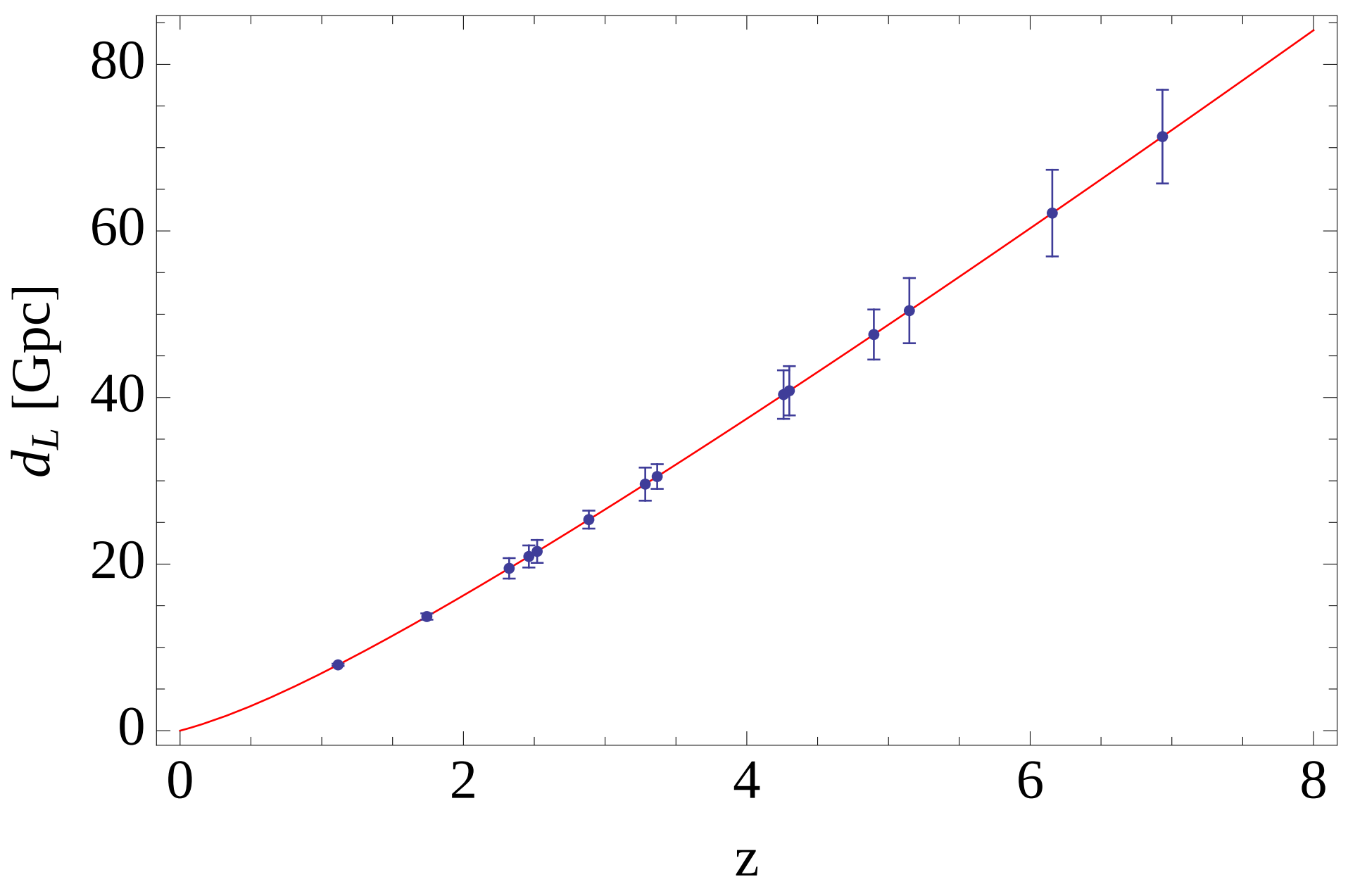
In order to determine how many standard sirens eLISA will observe and at what level it will be able to constrain the cosmological parameters, we adopted the following realistic approach [1]:

- We started by simulating massive black hole binary (MBHB) mergers in the Universe over a period of 5 years (the mission duration) taking into account three different astrophysical models for the formation and evolution of massive black holes.
- We computed for how many of these mergers there will be a GW signal detected by eLISA (with SNR>8)
- Among all these detections we selected the ones sufficiently localised in the sky ($d\Omega < 10\,\mathrm{deg}^2$)
- For the remaining events we estimated the amount of EM emissions at merger employing available results from MBHB numerical simulations and using the data available from our own simulation of MBHB evolution
- We predicted how many of these counterparts will be observed by next generation EM telescopes, such as LSST, E-ELT and SKA
- Finally we fitted the data obtained from these standard sirens with the distance-redshift relation theoretically calculated using different cosmological models

Results



The figure on the left shows the number of standard sirens that eLISA will be able to observe in combination with future EM telescopes, according to the analysis outlined above. From left to right are listed different eLISA design configurations varying the number of active laser links between 4 (2 arms) and 6 (3 arms) (L4, L6), the arm-length between 1, 2 and 5 million km (A1, A2, A3) and the low-frequency noise between the LISA pathfinder expected result and another one a factor of ten worst (N2, N1). From the figure it is clear that only 3-arm configurations will be able to provide the sufficient number of standard sirens (~ 15) needed for an independent probe of the cosmological expansion, while for 2-arm configurations it will not be possible to do late-time cosmology with eLISA. This strongly depends on the fact that 3-arm configurations better localise GW sources if compared to 2-arm ones.



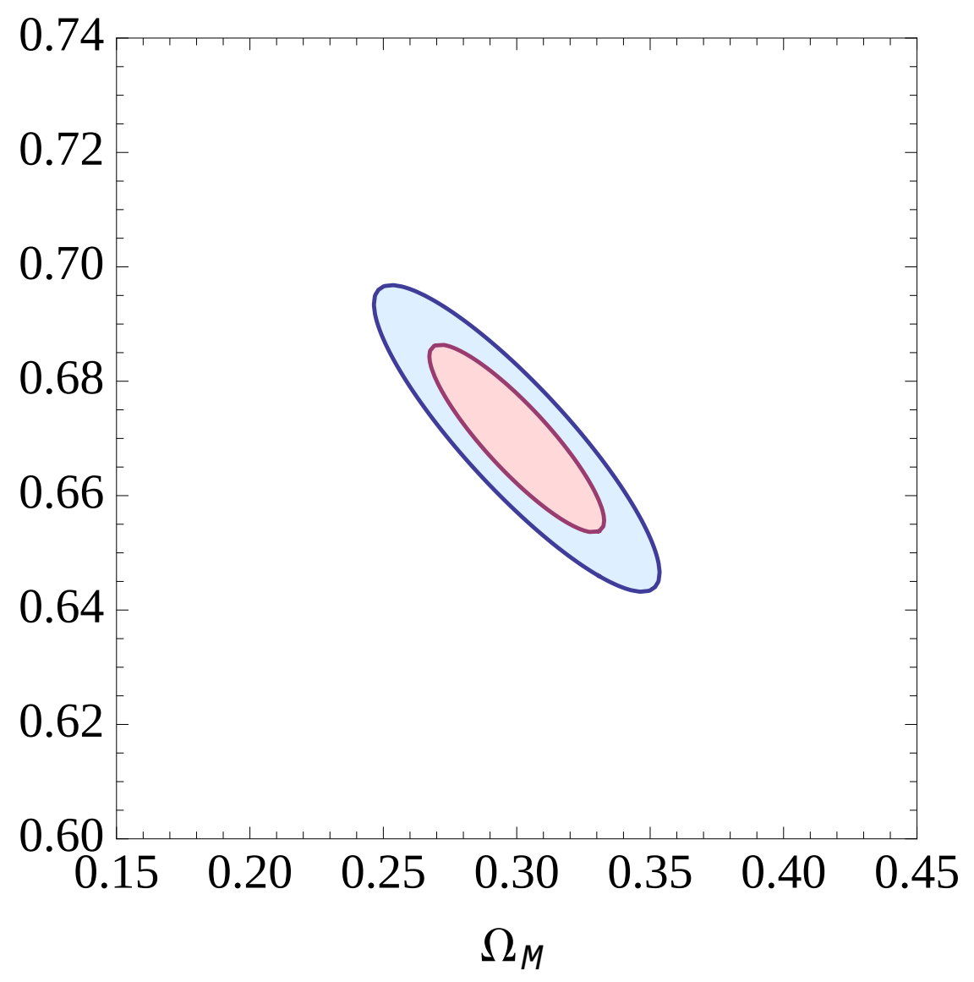
An example of standard sirens data coming from one of our simulations is provided in the figure on the left. From the figure one can realise that eLISA will be able to directly probe the expansion of the universe at very high redshifts, up to $z \sim 8$. Despite the lower number of data point, this constitutes the main advantage of MBHM standard sirens with respect to SNIa which can only reach $z \sim 2$.

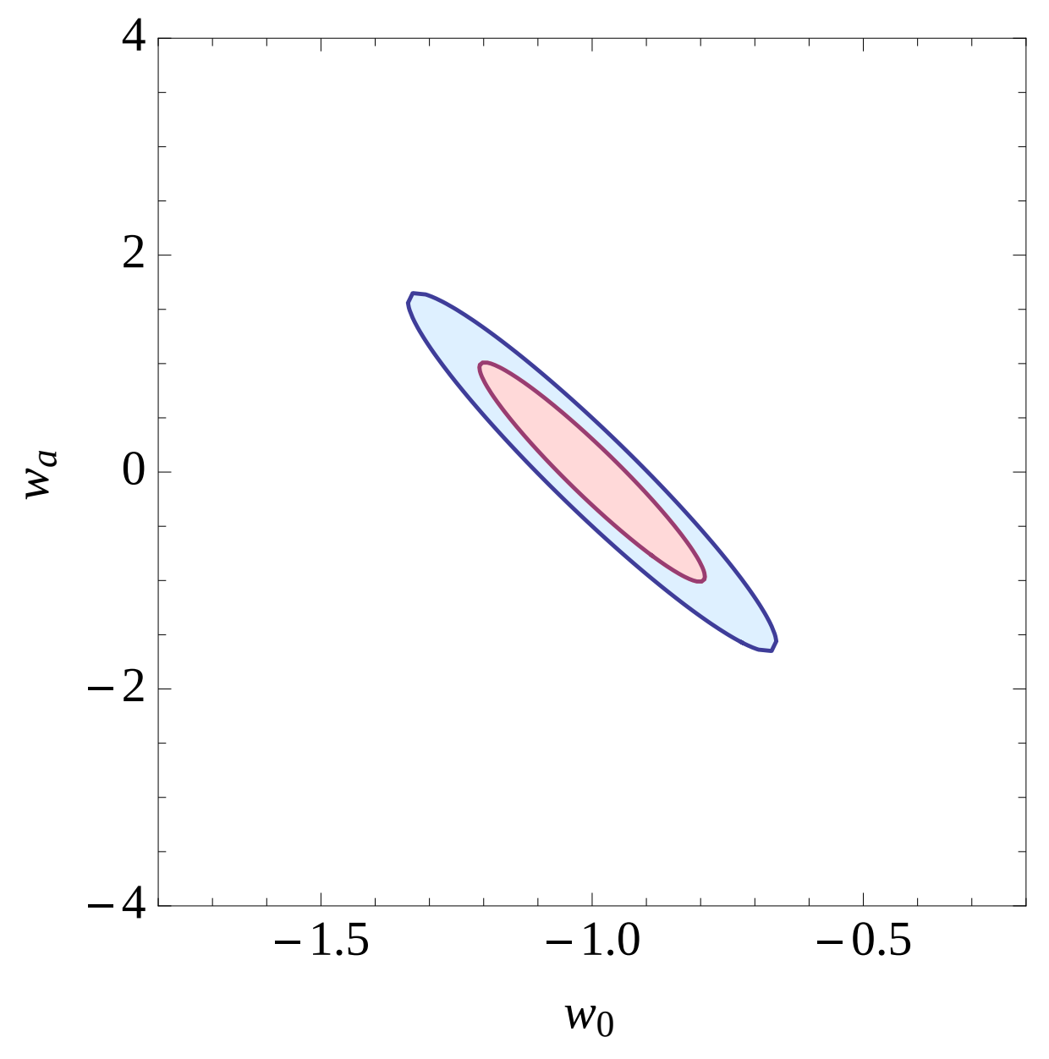
The forecast constraints obtained with the best possible configuration (N2A5M5L6) are listed below for three different cosmological models: ΛCDM, ΛCDM plus curvature and dynamical dark energy. In the latter all ΛCDM parameters are fixed and the equation of state of dark energy is parametrised by $w = w_0 + w_a z/(1+z)$. One and two sigma contour plots are also showed below for different pairs of parameters in one of the astrophysical MBHB model considered (light seeds – popIII). The constraints below are slightly worst than present CMB constraints, but are much better than present SNIa constraints. The same level of accuracy can be reached if the eLISA arm-length is changed to shorter values (A1 or A2), but if the noise (N1) or the number of laser links (L4) are different then they degrade considerably, especially in the latter case. An interesting result is the percent level constraint that eLISA will set over the Hubble constant H_0, possibly solving the current tension on this parameter between local and CMB observations.

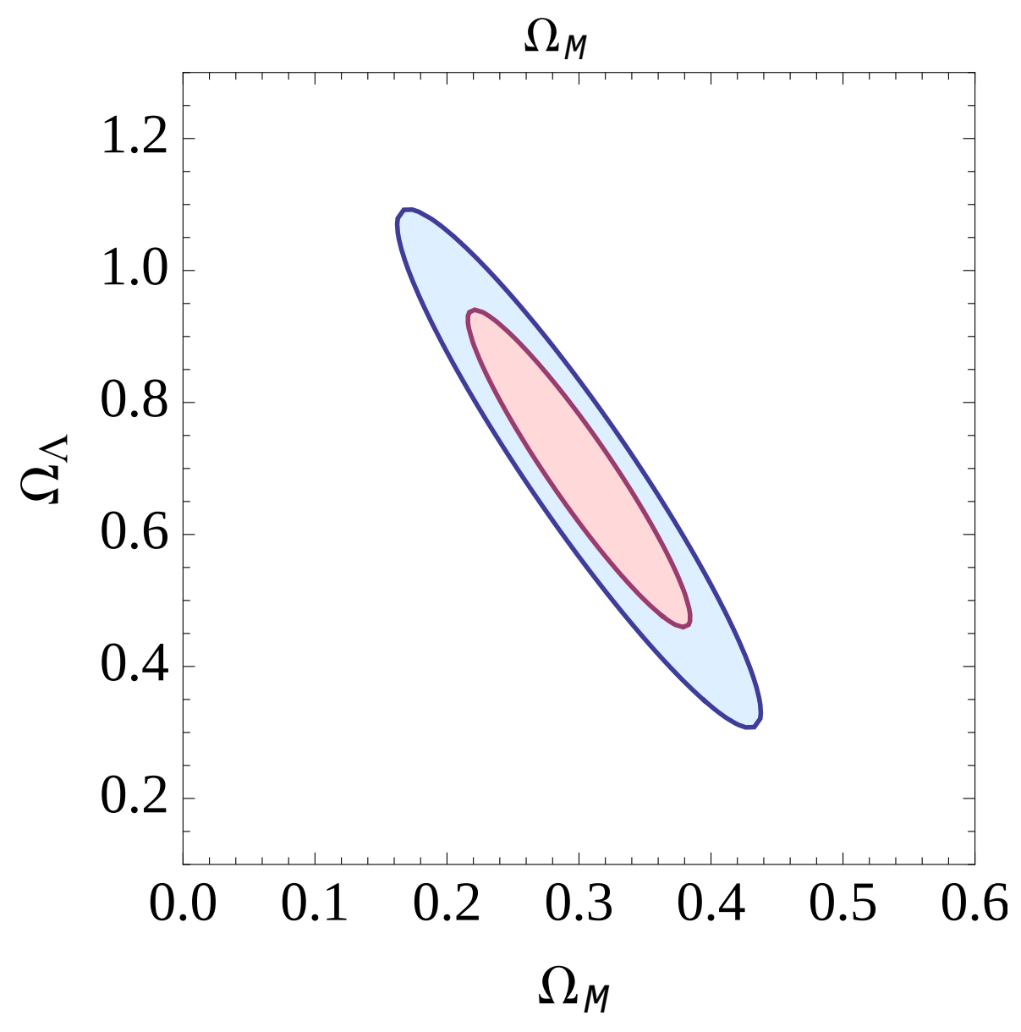
$$\textbf{ΛCDM:}\quad \begin{cases} \Delta\Omega_M & \simeq 0.025 \quad (8\%) \\ \Delta h & \simeq 0.013 \quad (2\%) \end{cases}$$

$$\textbf{ΛCDM + curvature:}\quad \begin{cases} \Delta\Omega_M & \simeq 0.054 \quad (18\%) \\ \Delta\Omega_\Lambda & \simeq 0.15 \quad (21\%) \\ \Delta h & \simeq 0.033 \quad (5\%) \end{cases}$$

$$\textbf{Dynamical DE:}\quad \begin{cases} \Delta w_0 & \simeq 0.16 \\ \Delta w_a & \simeq 0.83 \end{cases}$$







Conclusions

- In the new era of GW astronomy it will be possible to map the expansion of the universe using GW standard sirens
- Although the distance can be extracted directly from the GW waveform, the main problem will be to observe an EM counterpart to measure the redshift of the source
- MBHB merger events represent excellent standard sirens for eLISA, capable of providing data at very high redshifts (up to ~ 8)
- eLISA will thus be able to probe the expansion of the Universe in a region not accessible by SNIa
- Forecast constraints for eLISA on standard cosmological parameters are better than present SNIa observations and comparable to present CMB measurements

References

[1] Nicola Tamanini, Chiara Caprini, Enrico Barausse, Alberto Sesana, Antoine Klein, and Antoine Petiteau. Science with the space-based interferometer eLISA. III: Probing the expansion of the Universe using gravitational wave standard sirens. *JCAP*, 1604(04):002, 2016. arXiv:1601.07112.